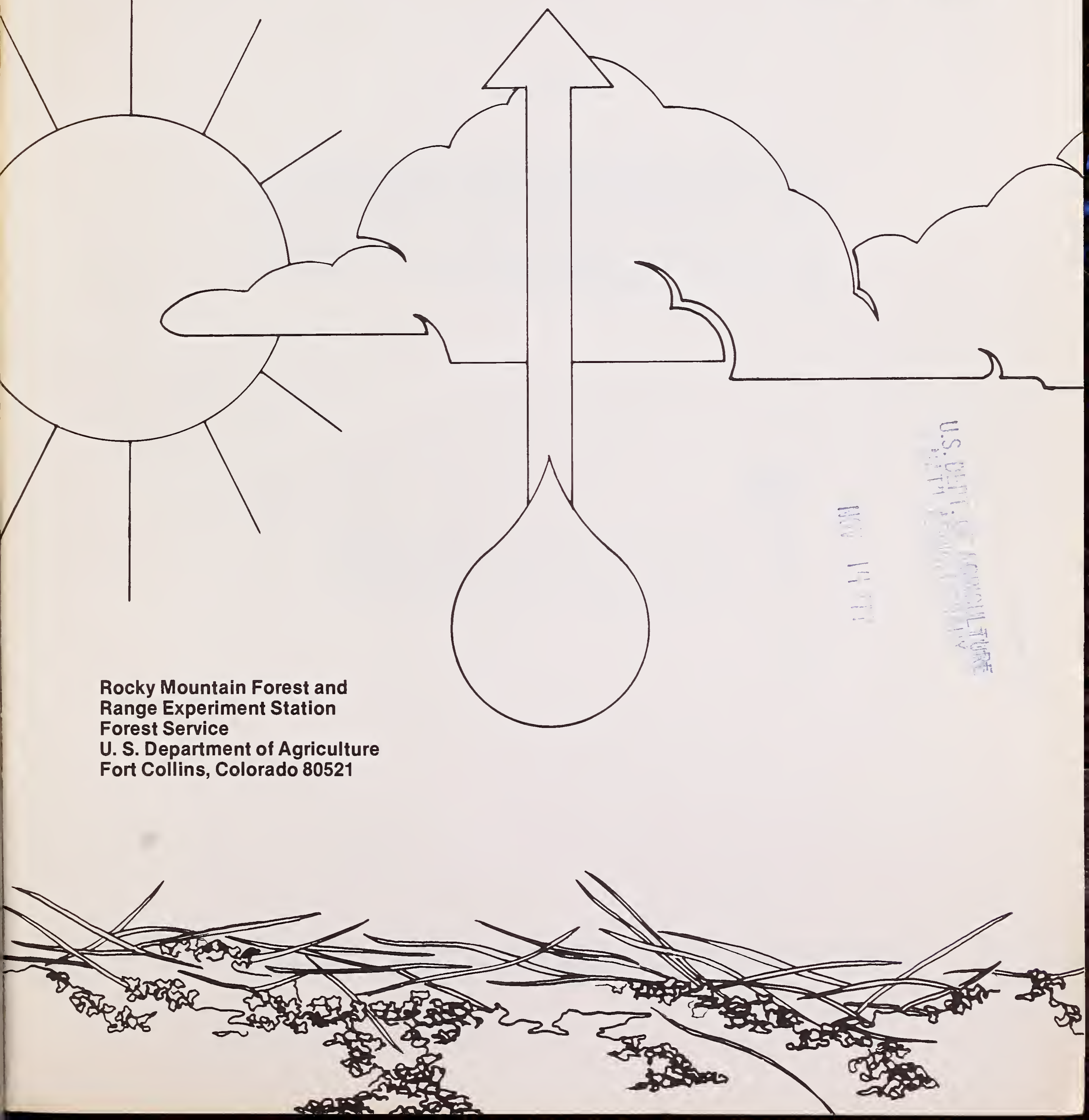
USDA Forest Service
Research Paper RM-195
November 1977

Heat and Water Transport Properties in Conifer Duff and Humus

Michael A. Fosberg



Rocky Mountain Forest and
Range Experiment Station
Forest Service
U. S. Department of Agriculture
Fort Collins, Colorado 80521

Abstract

Permeability and bulk densities of duff and humus in stands of ponderosa pine, lodgepole pine, and Douglas-fir were measured to provide a data base for fuel moisture and soil infiltration models. Diffusion of heat and water vapor through a ponderosa pine duff layer was measured to calibrate a diffusion model. These results provide necessary data and relationships required by complex forest soil water balance and energy models.

USDA Forest Service
Research Paper RM-195

November 1977

Heat and Water Transport Properties in Conifer Duff and Humus

Michael A. Fosberg[1]

[1]Principal Meteorologist, Rocky Mountain Forest and Range Experiment Station, with central headquarters maintained at Fort Collins, in cooperation with Colorado State University.

Heat and Water Transport Properties in Conifer Duff and Humus

Michael A. Fosberg

Introduction

Heat and water movement in forest soils are integral parts of many forestry-oriented models. Knowledge of infiltration is a basic requirement of hydrologic and ecological prediction models, although soil moisture also is important in engineering through analysis of soil stability. Influence of soil moisture, primarily the upper horizons (L, F and H), on fire danger and fire management require detailed and accurate prediction. While fire receives the major emphasis in this paper, applications to other forest management activities also are included.

Prediction of heat and mass flux in forest soils with models based on physical processes almost always requires soil structural data which can not be measured readily. The most practical procedure to develop this necessary data base would be to develop similitude relationships between the easily measured characteristics of depth and bulk density and those properties of timelag, permeability, and thermal conductivity required in the fluid and thermal flux models.

Many bulk density measurements have been made for litter, duff, and humus under most of the major conifer species and some of the deciduous species (Van Wagner 1970; Stocks 1970; Brown 1966, 1970a; Anderson 1969; Davis et al. 1968; Ffolliott et al. 1968). Laboratory measurements of particle characteristics such as surface area to volume ratios, moisture and thermal timelags and particle densities (Brown 1970a, 1970b; Mutch and Gastineau 1970; Fosberg et al. 1970; USDA Forest Service 1966; Anderson et al. 1976; Blackmarr 1972; Van Wagner 1969) have been made. In addition, several studies have been carried out on flux properties of forest soils or on sorbing porous media which describe heat and moisture flux of specific litter, duff, or humus layers (Nelson 1969; Anderson et al. 1976; Van Wagner 1970; Johnson 1968; Jarvis and Tucker 1968; McLeoud 1976; Murano and Lawson 1970). A few studies have included measurements of parameters such as the void volume per amount of surface area (Anderson 1969; Brown 1970a) which can be directly related to the mass and energy flux parameters. These data from the literature along with data collected in this study were combined to develop methods to calculate timelag and infiltration parameters required by heat and mass flux models.

Theoretical Basis for Data Relationships

Three types of relationships can be defined to interrelate variables or groups of variables. The first type, called state relationships, is based on the fundamental definition of the individual parameters. A second type, defined as dynamic relationships, relate flux parameters to the individual parameters. The third type introduces time-dependent processes and relates the state and dynamic relationships to time-dependent characteristics such as timelag. This type will be called similitude relationships.

State Relationships

Five basic particle and horizon characteristics defining the soil structure are required to describe the state relationships and to calculate combinational state characteristics. These structural characteristics are particle surface area to volume ratio (σ), particle density (ϱ_P), porosity (ϕ), bulk density of the horizon (ϱ_B), and thickness of a horizon (H). The first two characteristics define the particle properties and are readily measured in the laboratory. In forest soils, these properties in the litter, duff, and humus layers are fairly constant and can be related to the plants on the site. The last three characteristics define the way these particles are assembled in a soil horizon and are measured in the field.

Procedures and techniques for measuring these properties are described elsewhere (Brown 1970a, 1970b; Siau 1971). A complete set of definitions and elementary manipulations are given in the Appendix.

State relationships require detailed laboratory measurements of particle density (ϱ_p) and surface area to volume ratio (σ). Because these characteristics are well known and are reasonably constant, only field measurements of bulk density and horizon thickness are required. Since bulk density measurements for individual horizon are also reasonably constant, field measurements of horizon thickness and total mass of the horizon per unit area (fuel loading) along with detailed laboratory measurements of particle density, surface area to volume ratio, and specific heat fully describe the state relationships.

Dynamic Relationships

Dynamic relationships between the state relationships and flux properties are based on analysis of the influence of a particular state relationship on mass or heat transport in soils when external controls are held constant and the flux achieves a steady state equilibrium. These are theoretical, idealized relationships between the state relationships and the flux properties of hydraulic conductivity and the void diffusivities. Mass flux is based on assumptions involving the state relationships of porosity, internal surface area, and a tortuosity factor which describes aggregate porosity microvariations. Hydraulic conductivity of individual horizons is readily measured. To relate these measurements to the state relationships, the Kozney permeability (Fair and Hatch 1933; Childs and Collis-George 1950) model was used. The intrinsic permeability is

$$K = \frac{a\phi^3}{(1-\phi)^2\sigma^2} \qquad (1)$$

where "a" is an arbitrary constant. Intrinsic permeability, with units of area, is converted to hydraulic conductivity, with units of velocity through the Darcy equation relationship

$$K' = \frac{K\,\partial p}{\eta\,\partial L} \qquad (2)$$

where η is the viscosity, and $\partial p/\partial L$ is a unit drop in hydraulic head. For water, $K' = 1$ cm/sec corresponds to 1.02×10^{-5} cm^2.

Similitude Relationships

Characterization of nonsteady-state heat and mass flux requires a time variable. The traditional time variable used in similitude relationships is the timelag or time response of a system to an instantaneous change from one environmental state to another. Such responses generally follow negative exponential function and are characterized by negative integer exponents of e (i.e., the time to reach e^{-1} of response is the first timelag; the time between the value at e^{-1} and e^{-2} is the second timelag, etc.). Only rarely are the individual timelags equal between the first and last (e^{-n}) because of hystereisis or differential responses to external forces.

Similitude relationships describe time-dependent diffusion processes in forest soils. The first, the Fourier number (Luikov 1966) for heat transfer and the corresponding relationship for moisture flux, is

$$F_h = \frac{\varkappa\,\tau_h}{H^2} \approx 0.14 \qquad (3a)$$

for heat transfer, and

$$F_m = \frac{\nu\,\tau_m}{H^2} \approx 0.18 \qquad (3b)$$

for moisture flux, where $\varkappa$ is the thermal diffusivity, τ_h is the heat flux timelag, H is the thickness of the layer, ν is the moisture diffusivity, and τ_m is the moisture timelag. The similitude numbers in equations 3a and 3b were obtained from Fosberg et al. (1970) and Fosberg (1973), respectively. These similitude relations describe bulk characteristics of the diffusion process but do not describe details of the physical processes (i.e., mass and energy transferred in the voids as opposed to that transferred in the particles). These relationships are general, however, since they are valid for bulk properties in both sorbing and nonsorbing porous media.

A second set of similitude relationships which are specific to sorbing porous media, and which are more specifically related to the physical processes have been defined (Fosberg 1975). Structural properties, namely the porosity, are included in these similitude numbers. Also, the thermal and moisture timelags of the particles are included in those numbers. These numbers reflect the storage and slow uptake or release of

heat and moisture to the voids. The expression for moisture

$$F_m = \frac{\tau_m \, \nu^{2/3}}{H^{4/3} \, \tau_{pm}^{1/3} \, (1-\phi)} \qquad (3c)$$

breaks down for nonsorbing particles or when the particle timelag becomes very short since the horizon timelag is limited at the low end by molecular diffusion through the voids. Heat transfer for sorbing materials is similarly

$$F_h = \frac{\tau_h \, \varkappa^{2/3}}{H^{4/3} \, \tau_{ph}^{1/3} \, (1-\phi)} \qquad (3d)$$

where τ_m and τ_h are the horizon timelags for moisture and heat, H is the horizon thickness, and τ_{pm} and τ_{ph} are the particle timelags for moisture and heat. This relationship also breaks down when heat conduction between particles becomes important and the storage, uptake, and release of heat becomes small. These last two relationships most appropriately describe vapor and heat transport through litter, duff, and humus layers. The Fourier number relationships, while describing all horizons, are the best estimators of diffusion processes in nonsorbing horizons.

To provide a data base for modeling heat and mass flow through porous media, data from the literature and this study have been combined to calculate the flux properties. The basis for combining the observations to obtain flux characteristics is defined by the state, dynamic, and similitude relationships.

Experimental Procedures

Two separate sets of experiments were carried out to calibrate the dynamic and similitude equations previously described. The first experiment was designed to calibrate the permeability equation to make infiltration calculations. The second experiment was to determine the thermal and moisture timelags of individual duff layers, and was to estimate the similitude numbers.

Permeability and Bulk Density Measurements

Samples of duff and humus layers were taken from under ponderosa pine (*Pinus ponderosa* Laws), lodgepole pine (*Pinus contorta* Doug), and Douglas-fir (*Pseudotsuga menziesii* (Mirb) Franco) on the Manitou Experimental Forest near Woodland Park, Colo. to establish the Kozney constant in the permeability equation. Sample holders were cut from standard snow tubes with an inside diameter of 5.804 cm and a length of 5.230 cm. One end of each sample tube was beveled to a sharp edge. By carefully trimming the duff and humus against this edge, the sample tube could drop through the horizon without disrupting the natural structure. Since the intent of this experiment was to determine heat and mass flux characteristics, small twigs, bark platelets and other nonneedle material were not removed from the sample.

Tube depth (5.230 cm) somewhat restricted sampling location to those sites having individual horizons of at least this thickness since the tubes must be filled to reduce error in the permeability measurements. These restrictions biased the results to horizons in high basal area or dense stands and to near tree-base locations. They did insure, however, that sample tubes contained only material from a single horizon, and that the results could be considered to be "homogeneous" from the standpoint of experimental replication.

Permeability measurements were made by measuring the pressure drop between the top and bottom of the sample tube. Samples were placed in a permeameter (fig. 1) which had a mesh screen support fine enough to prevent duff and humus particles from being drawn into the flow system. No pressure drop was induced by the screen. Air was drawn through the sample with a vacuum pump at a known flow rate. The pressure drop

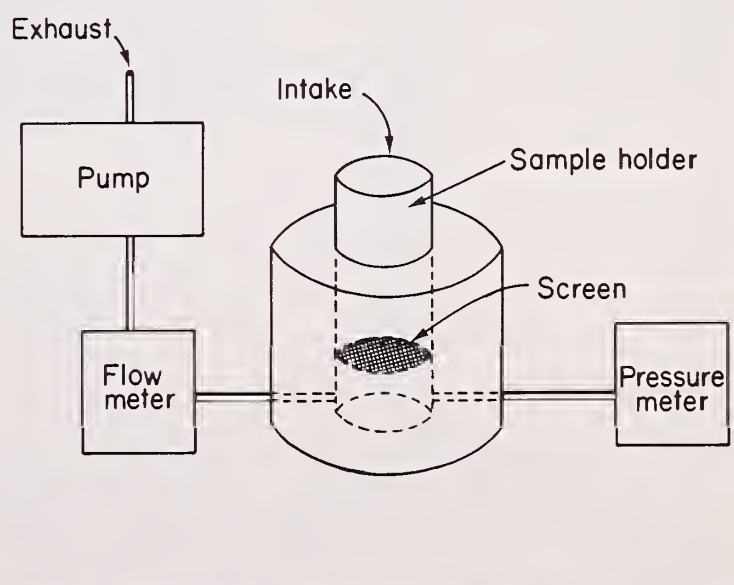


Figure 1.—Schematic of permeameter. Air is drawn through sample. Pressure drop is measured between free air and pressure at the bottom of the sample.

across the sample was measured with an EQUIBAR type 120 pressure meter. The permeability measuring system was constructed so that volumetric flow rate and pressure drop were measured at the downstream end of the flow system. Therefore, pressure fluctuations induced by the pump were minimal. Pressure drops through this open flow were typically a few tens of millimeters from free air pressure. A number of flow rates and corresponding pressure drops were measured for each sample. All permeability measurements were made in the morning to eliminate environmental pressure fluctuations from frequent afternoon thunderstorms. Intrinsic permeability was calculated by eq. (2).

Once permeability was determined for each sample, the container and intact samples were dried for 24 hr at 105°C to determine bulk density.

Eight samples of Douglas-fir duff, seven samples of Douglas-fir humus, eight samples of ponderosa pine duff, five samples of ponderosa pine humus and two samples each of lodgepole duff and humus were collected.

Heat and Vapor Flux Measurements in an Environmental Chamber

To determine heat and mass diffusion rates in duff, and to test the hypothesis that particle sorption properties control the diffusion rate rather than simple void-controlled diffusion, a two-compartment environmental chamber was constructed and instrumented for temperature, heat flux, and humidity. The chamber consisted of two plenums, each approximately 24 cm deep with a 51 by 41 cm interface (fig. 2). A ponderosa pine

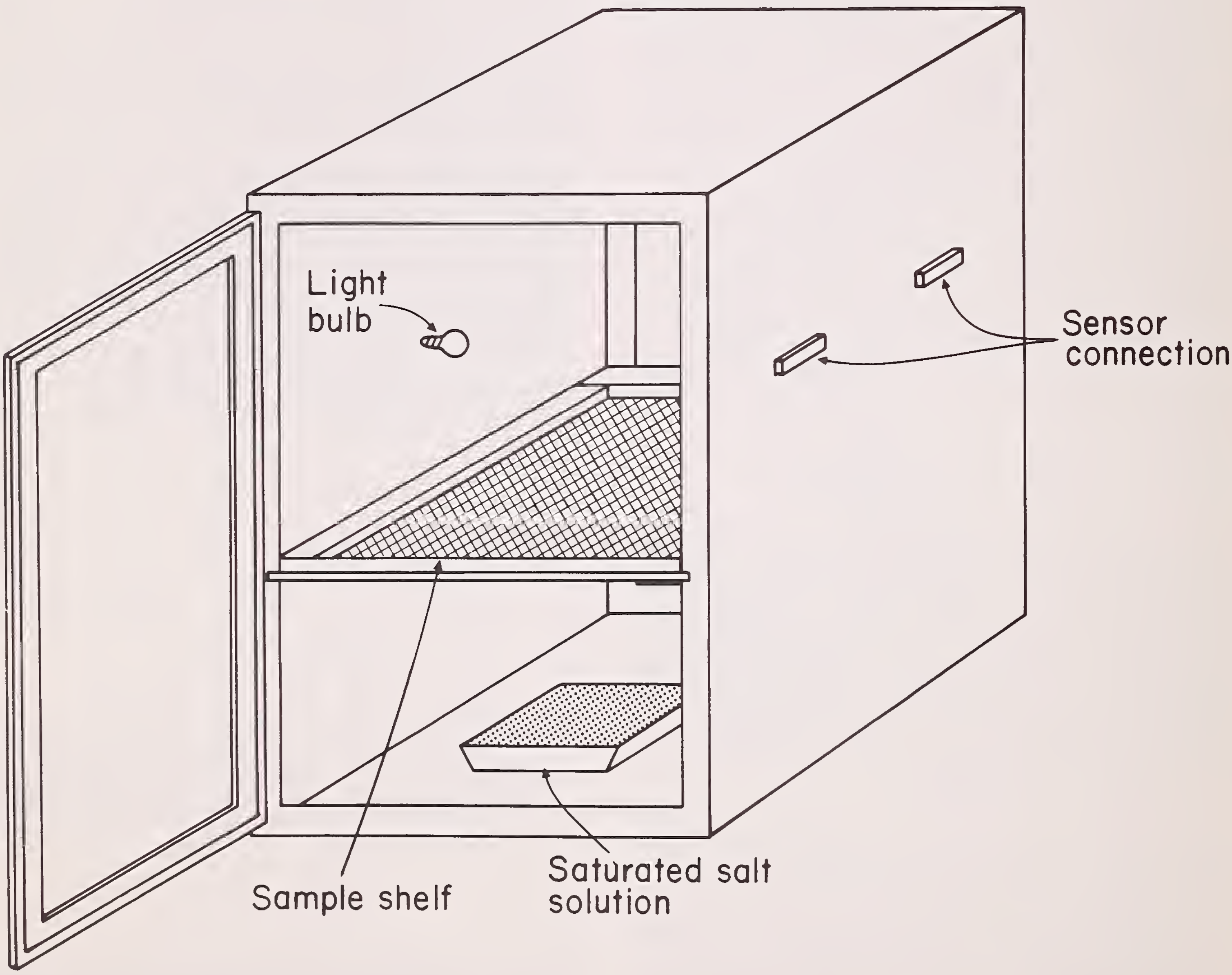


Figure 2.—Schematic of humidity cabinet. Sample of duff layer is placed on screen in the center of the cabinet.

duff layer 8.7 cm thick was placed on a screen shelf between the two plenums so that diffusion would take place only through the duff sample. This sample was lifted from the field as an intact horizon. A tight fitting metal lip around the screen edge prevented leakage. Thermistors were placed 2 cm above the duff layer in the upper plenum; on the upper surface; at distances 2.9, 3.0, 4.1, 4.9, and 5.6 cm from the top surface; on the bottom surface; and 2.2 cm below the sample in the lower plenum. Moisture content was measured with Delmhorst humidity probes. These wooden humidity sensors are 0.237 cm thick and have a response time of about 1 hr. The moisture probes were placed 1.9 cm above the top surface, on the top surface, and at distances 2.9, 3.7, 4.3, 4.6, and 5.2 cm from the top. Moisture probes also were placed at the lower surface of the duff and 2 cm below the sample in the plenum. A heat flux plate was placed 3.8 cm from the top surface. All sensors were located near the center of the sample to avoid any wall effects. The entire cabinet was insulated with 10-cm-thick foam rubber.

Two experiments were carried out. The first was set up to determine water vapor flux properties of the duff layer, specifically the moisture timelag and effective diffusivity of the layer. Effective diffusivity is used here to indicate the composite effect of sorption as well as transport processes. The duff sample was brought to an equilibrium moisture condition with a saturated salt solution of $NaClO_3$ at 20°C to produce a uniform relative humidity of 75%. Once the sample attained moisture equilibrium, it was held at that condition for 48 hr before beginning the desorption test. A saturated salt solution of $CaCl_2 \cdot 6H_2O$ (equilibrium relative humidity of 32% at 20°C) was placed in the lower plenum, and the $NaClO_3$ salt solutions were removed. Humidity was monitored on all sensors at 20-min intervals for 96 hr.

The second experiment was to determine the thermal timelag and heat flux properties of the duff sample. The sample was conditioned with the $NaClO_3$ salt solution for 1 week. After this initial conditioning, a 60-watt light bulb in the upper plenum was used as a heat source. Temperature was monitored at 2-min intervals, and heat flux was monitored continuously for 6 hr.

Results

Intrinsic permeability was calculated from the pressure drop and flow rates with eq. (2). After appropriate unit conversion

$$K = \frac{v \eta 1}{\Delta p} = 6.936 \times 10^{-7}\, v/\Delta p \quad (4)$$

where v is in cm/sec, Δp is in mm of Hg, and K is in cm^2. The relationship between permeability and readily measured properties such as bulk density or other parameters used in fire behavior models was evaluated through the Kozney formulations of permeability. Measured bulk densities were combined with data (Anderson 1969, Brown 1970) on surface area to volume ratio and density of particles to calculate porosity. These transformed data were used to calculate the calibration coefficient in Kozney's equation (table 1). Bulk density of duff layers ranged from 0.06 to 0.12 gm/cm^3 while the permeability ranged over an order of magnitude (from 10^{-3} cm^2 to 10^{-4} cm^2). As bulk density increased, permeability decreased. Humus samples had permeabilities much lower than duff, ranging from 10^{-5} cm^2 to 10^{-6} cm^2. Also, bulk densities for the humus sample ranged from 0.1 gm/cm^3 to 0.36 gm/cm^3 and showed a much stronger density influence on permeability than did the duff. Combining all duff samples into a single regression equation of permeability, versus the group of variables $(\phi^3/(1-\phi)^2\ \sigma^2)$, the slope (Kozney coefficient) was $2.81 \times 10^{-2} \pm 1.5 \times 10^{-2}$, where the range is expressed as a standard error of estimate. The corresponding slope for humus was $4.16 \times 10^{-2} \pm 1.9 \times 10^{-2}$.

Diffusion and sorption experiments in the environmental chamber were evaluated from integral moisture contents measured by the Delmhorst moisture probes and internal temperature measured with thermistors. Both temperature and moisture content were transformed to nondimensional variables of actual value less the final value divided by the initial value less the final value,

$$\frac{T - T_f}{T_O - T_f}$$

and

$$\frac{M - M_f}{M_O - M_f}$$

These ratios, as a function of time (fig. 3 and 4), approximated a straight line in a log-linear graph, indicating that a timelag could be determined for both moisture and temperature. Moisture timelag was determined to average 50 hr for the 8.7 cm duff layer (fig. 3) and the thermal timelag was found to be 1.45 hr. Calculation with eq. (3a) and

Table 1.--Characteristics of duff and humus samples.

Sample	Bulk density ρ_B	Particle density ρ_p	Surface area and volume ratio σ	Packing ratio β	Porosity ϕ	Permeability K	Kozney Constant a
	g/cm^3	g/cm^3	cm^{-1}	*Dimensionless*	*Dimensionless*	cm^2	*Dimensionless*
Douglas-fir duff:							
	0.098	0.6	69.1	0.163	0.834	1.2×10^{-4}	2.62×10^{-2}
	.098	.6	69.1	.163	.834	9.6×10^{-6}	2.10×10^{-2}
	.096	.6	69.1	.160	.840	8.4×10^{-6}	1.73×10^{-2}
	.085	.6	69.1	.142	.858	1.6×10^{-4}	2.44×10^{-2}
	.118	.6	69.1	.197	.803	1.7×10^{-4}	6.08×10^{-2}
	.097	.6	69.1	.162	.838	8.2×10^{-5}	1.75×10^{-2}
	.082	.6	69.1	.137	.863	1.2×10^{-4}	1.67×10^{-2}
	.073	.6	69.1	.122	.878	1.6×10^{-4}	1.56×10^{-2}
Ponderosa pine humus:							
	.233	.47	100	.496	.504	8.1×10^{-7}	1.56×10^{-2}
	.256	.47	100	.545	.455	1.1×10^{-6}	3.47×10^{-2}
	.258	.47	100	.549	.451	1.6×10^{-6}	5.26×10^{-2}
	.301	.47	100	.640	.360	4.1×10^{-6}	3.60×10^{-1}
	.272	.47	100	.579	.421	4.4×10^{-6}	1.98×10^{-1}
Lodgepole pine humus:							
	.176	.56	100	.314	.686	6.8×10^{-6}	2.08×10^{-2}
	.366	.56	100	.654	.346	5.2×10^{-7}	5.37×10^{-2}
Douglas-fir humus:							
	.111	.6	300	.185	.815	9.0×10^{-6}	5.69×10^{-2}
	.121	.6	300	.202	.798	7.6×10^{-6}	6.10×10^{-2}
	.119	.6	300	.198	.802	2.1×10^{-6}	1.60×10^{-2}
	.121	.6	300	.202	.798	6.3×10^{-6}	5.06×10^{-2}
	.106	.6	300	.177	.823	4.1×10^{-6}	2.30×10^{-2}
	.160	.6	300	.267	.733	3.9×10^{-6}	7.06×10^{-2}
	.128	.6	300	.213	.787	4.7×10^{-6}	4.37×10^{-2}
Ponderosa pine duff:							
	.100	.51	57.6	.196	.804	1.1×10^{-4}	2.71×10^{-2}
	.104	.51	57.6	.204	.796	8.1×10^{-5}	2.22×10^{-2}
	.078	.51	57.6	.153	.847	2.7×10^{-4}	3.45×10^{-2}
	.080	.51	57.6	.157	.843	1.9×10^{-4}	2.59×10^{-2}
	.065	.51	57.6	.127	.873	5.3×10^{-4}	4.26×10^{-2}
	.059	.51	57.6	.116	.884	5.1×10^{-4}	3.30×10^{-2}
	.089	.51	57.6	.175	.825	5.1×10^{-5}	9.23×10^{-3}
	.077	.51	57.6	.151	.849	7.3×10^{-5}	9.02×10^{-3}
Lodgepole pine duff:							
	.079	.56	64.7	.141	.859	3.6×10^{-4}	4.73×10^{-2}
	.115	.56	64.7	.205	.795	1.6×10^{-4}	5.60×10^{-2}

(3b) yielded effective diffusivities of 7.5×10^{-5} cm^2/sec and 2.03 cm^2/sec respectively for water vapor and heat.

Thermal conductivity of the duff layer was measured near the end of the heat flux experiment after a reasonably constant temperature gradient had been established (a variation of less than 0.1 °C/cm hr). The thermal conductivity was found to be 2.67×10^{-5} cal/(cm sec C).

Similitude relations expressed in eq. (3c) and (3d) can be used to calculate horizon timelags. Using horizon timelags measured in this experi-

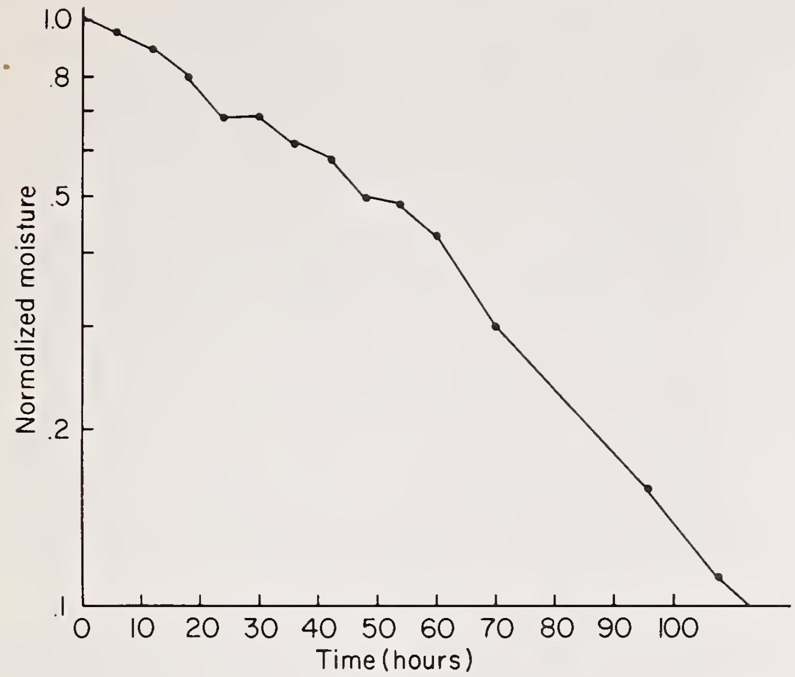


Figure 3.—Desorption of ponderosa pine duff layer. Average timelag is 50 hr.

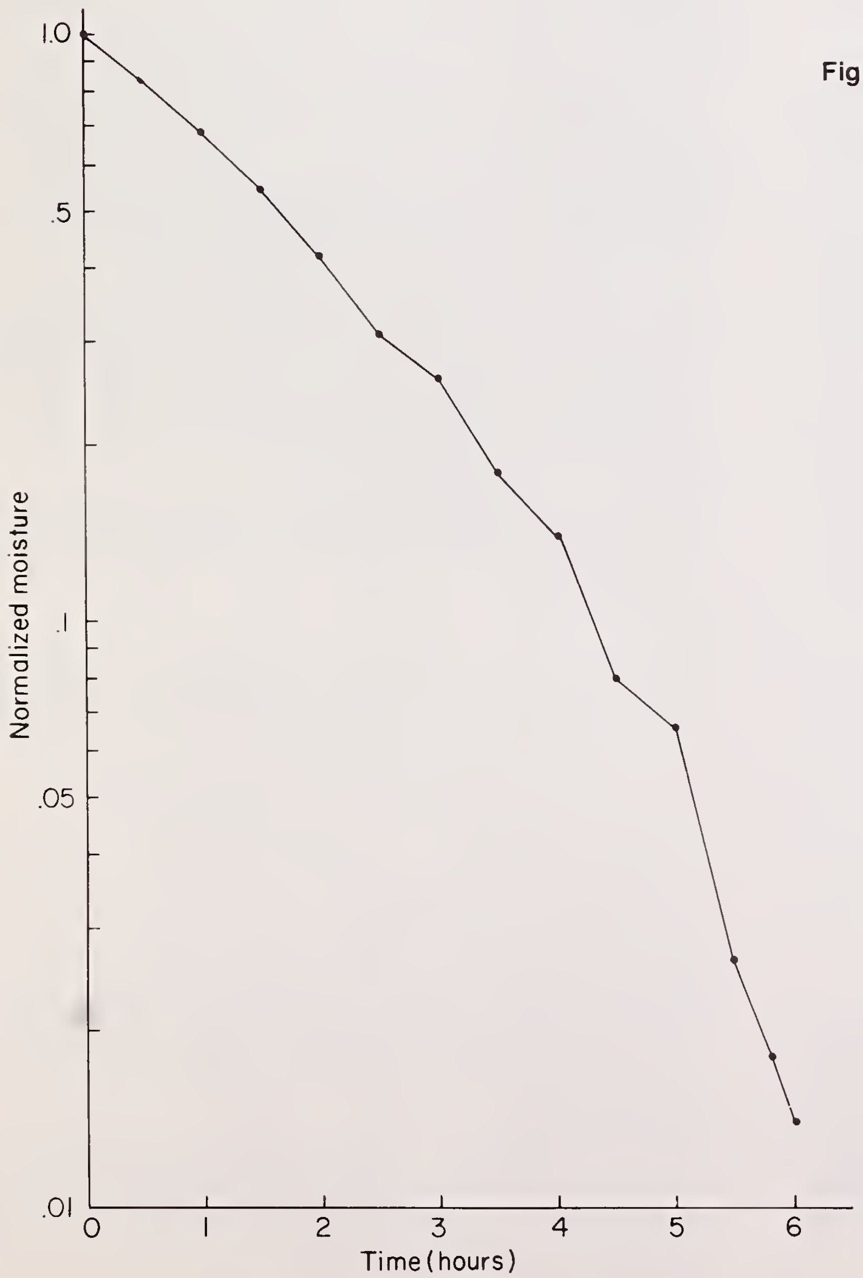


Figure 4.—Normalized temperature change of ponderosa pine duff. Average timelag is 1.46 hr.

ment, along with particle timelags for ponderosa duff particles, the similitude number for moisture was 1572, and for heat was 1438. It should be emphasized that these numbers are from a single experiment; therefore, they may not be universal.

Summary

Hydraulic conductivities of duff and humus are large, ranging from a few tenths of a centimeter per second to as much as 30 cm per second. An attempt to predict these hydraulic conductivities from the readily measured property of bulk density met with marginal success in that the standard error of the prediction equation yields a 50% uncertainty in the hydraulic conductivity. While the error is large, so is the conductivity in relation to precipitation rates, and the two horizons will not impede infiltration. Any puddling of water in these horizons must come from water standing above less permeable substrata.

A single pair of experiments on heat and water vapor diffusion through a ponderosa pine duff layer support the concept that heat and water vapor transport rates through litter, duff, and humus are regulated by the sorption properties of the organic materials. The timelags which would be expected from these layers, if the material were perfectly inert to the heat and vapor content of the voids, would be very short. Reduction of the diffusivities according to eq. (2c) and (2b) in the appendix is slight. Observations of large hydraulic conductivities in these horizons would lead to the idea of short timelag. Measured timelags are much larger, and calculated effective diffusivities are much lower by several orders of magnitude than would be expected from an inert solid. Direct measurements of thermal conductivities also show this reduction of heat flux. The implication is that the transport of heat and water vapor by diffusion is controlled by the storage capabilities of the particles, and that source-sink terms must be included in the traditional input-through flow-output models for these horizons.

Results from this limited heat and water vapor diffusion experiment qualitatively support the hypothetical model. Little quantitative can be said because of the limited data. More confidence can be placed on the hydraulic conductivities, however, because of the substantial number of samples.

Literature Cited

Anderson, Hal E. 1969. Heat transfer and fire spread. USDA For. Serv. Res. Pap. INT-69, 20 p. Intermt. For. and Range Exp. Stn., Ogden, Utah.

Anderson, Hal E., Robert W. Mutch and Robert D. Schuette. 1976. Timelag and equilibrium moisture content of ponderosa pine needles. USDA For. Serv. Res. Pap., Intermt. For. and Range Exp. Stn., Ogden, Utah [in press].

Blackmarr, W. H. 1972. Personal correspondence.

Brown, James K. 1966. Forest floor fuels in red and jack pine stands. U. S. For. Serv. Res. Note NC-9, 3 p. North Central For. and Range Exp. Stn., St. Paul, Minn.

Brown, James K. 1970a. Physical fuel properties of ponderosa pine forest floors and choatgrass. USDA For. Serv. Res. Pap. INT-74, 16 p. Intermt. For. and Range Exp. Stn., Ogden, Utah.

Brown, James K. 1970b. Ratios of surface areas to volume for common fine fuels. For. Sci. 16:101-105.

Childs, E. C. and N. Collis-George. 1950. The permeability of porous materials. *In:* Proc. of Royal Society, Series A. 201:392-405.

Davis, James R., Peter F. Ffolliott and Warren P. Clary. 1968. A fire prescription for consuming ponderosa pine duff. U. S. For. Serv. Res. Note RM-115, 4 p. Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo.

Fair, G. M. and L. P. Hatch. 1933. Fundamental factors governing the streamline flow of water through sand. J. Am. Water Works Assoc. 26:1551-1665.

Ffolliott, Peter F., Warren P. Clary and James R. Davis. 1968. Some characteristics of the forest floor under ponderosa pine in Arizona. USDA For. Serv. Res. Note RM-127, 4 p. Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo.

Fosberg, Michael A. 1973. Prediction of prepyroysis temperature rise in dead forest fuels. Fire Technol. 9:182-188.

Fosberg, Michael A. 1975. Heat and water vapor flux in conifer litter and duff: A theoretical model. USDA For. Serv. Res. Pap. RM-152, 23 p. Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo.

Fosberg, Michael A., Robert W. Mutch and Hal E. Anderson. 1970. Laboratory and theoretical comparison of desorption in ponderosa pine dowels. Wood Sci. 3:94-99.

Jarvis, J. and R. E. Tucker. 1968. Drought index as a predictor of moisture content in L and F horizons on an upland white spruce-trembling aspen cut-over area. For. Branch Dey Publ. 1237, 10 p.

Johnson, Von J. 1968. Buildup index as an expression of moisture content in duff. USDA For. Serv. Res. Note NC-43, 4 p. North Central For. and Range Exp. Stn., St. Paul, Minn.

Luikov, A. V. 1966. Heat and mass transfer in capillary porous bodies. Pergamon Press, New York, 523 p.

McLeoud, Bruce. 1974. A direct fuel moisture measuring instrument: An aid for scheduling prescribed fires. *In:* Proc. Tall Timbers Fire Geol. Conf., Oct. 8-10, 1974. p. 609-626.

Millington, R. J. 1959. Gas diffusion in porous media. Science 130:100-102.

Millington, R. J. and R. C. Schearer. 1971. Diffusion in aggregated porous media. Soil Sci. 111:372-378.

Muraru, S. J. and B. D. Lawson. 1970. Prediction of duff moisture for prescribed burning. For. Res. Lab., Can. For. Serv. Inf. Rep. BC-X-46, 13 p.

Mutch, Robert W. and Orval W. Gastineau Jr. 1970. Timelag and equilibrium moisture content in reindeer lichen. USDA For. Serv. Res. Pap. INT-76, 8 p. Intermt. For. and Range Exp. Stn., Ogden, Utah.

Nelson, Ralph M. Jr. 1969. Some factors affecting the moisture timelags of woody materials. USDA For. Serv. Res. Pap. SE-44, 16 p. Southeastern For. and Range Exp. Stn., Asheville, N.C.

Penman, H. L. 1940. Gas and vapor movement in the soil I. the diffusion of vapors through porcus solids. J. Agric. Sci. 30:437-462.

Siau, John F. 1971. Flow in wood. Syracuse Univ. Press, Syracuse, N.Y. 131 p.

Stocks, B. J. 1970. Moisture in the forest floor—it's distribution and movement. Dep. of Fisheries and For., Can. For. Serv. Pub. 1271, 19 p.

U.S. Forest Service. 1966. Derivation of spread phase tables—national fire danger rating system. Div. of Fire Control, 54 p.

Van Wagner, C. E. 1969. Drying rates of some fine forest fuels. Fire Control Notes 30:5.

Van Wagner, C. E. 1970. An index to estimate the current moisture content of the forest floor. Dep. of Fisheries and For., Can. For. Serv. Publ. 1288, 23 p.

APPENDIX

Basic Definitions and Elementary Manipulations

1. State Variables—the properties are:

Surface area to volume ratio (σ)

$$= \frac{\text{Surface area of particle (S)}}{\text{Volume of particle }(V_p)}$$

Particle density (ϱ_p)

$$= \frac{\text{Mass of particle }(M_p)}{\text{Volume of particle }(V_p)}$$

Bulk density of horizon (ϱ_B)

$$= \frac{\text{Mass of particles }(M_p)}{\text{Volume of horizon }(V_B)}$$

Porosity of horizon (ϕ)

$$= \frac{\text{Volume of void space }(V_v)}{\text{Volume of horizon }(V_B)}$$

Thickness of horizon (H) = thickness of a homogeneous layer in which the above variables are constant.

These basic state variables are interrelated by the following definitions:

Volume of void space (V_v)

$$= \frac{\text{Volume of horizon }(V_B)}{-\text{Sum of particle volumes }(\Sigma V_p)}$$

Packing ratio (β)

$$= \frac{\text{Volume of particles in the horizon }(\Sigma V_p)}{\text{Volume of horizon }(V_B)}$$

Multiplying the basic definition of porosity by unity M_p/M_p,

$$\phi = \frac{\varrho_p - \varrho_B}{\varrho_p} \tag{1}$$

2. Dynamic Variables

Void diffusivities in porous media (Millington 1959; Millington and Schearer 1971; and Penman 1940) are reduced from free air values by the ratio

$$\frac{\nu}{\nu_0} = \frac{\varkappa}{\varkappa_0} = \phi^{2x} \tag{2a}$$

where ν and $\varkappa$ are the vapor and thermal diffusivities in the voids; ν_0 and $\varkappa_0$ are the corresponding values in the free air, ϕ is the state variables porosity, and x is a nondimensional tortuosity factor defined by the implicit function

$$\phi^{2x} - 1 + (1 - \phi)^x = 0 \tag{2b}$$

Fosberg, Michael A. 1977. Heat and water transport properties in conifer duff and humus. USDA For. Serv. Res. Pap. RM-195, 10 p. Rocky Mt. For. and Range Exp. Stn. Fort Collins, Colo.

Permeability and bulk densities of duff and humus in stands of ponderosa pine, lodgepole pine, and Douglas-fir were measured to provide a data base for fuel moisture and soil infiltration models. Diffusion of heat and water vapor through a ponderosa pine duff layer was measured to calibrate a diffusion model. These results provide necessary data and relationships required by complex forest soil water balance and energy models.

Keywords: Fuel moisture, soil infiltration, soil water balance.

Fosberg, Michael A. 1977. Heat and water transport properties in conifer duff and humus. USDA For. Serv. Res. Pap. RM-195, 10 p. Rocky Mt. For. and Range Exp. Stn. Fort Collins, Colo.

Permeability and bulk densities of duff and humus in stands of ponderosa pine, lodgepole pine, and Douglas-fir were measured to provide a data base for fuel moisture and soil infiltration models. Diffusion of heat and water vapor through a ponderosa pine duff layer was measured to calibrate a diffusion model. These results provide necessary data and relationships required by complex forest soil water balance and energy models.

Keywords: Fuel moisture, soil infiltration, soil water balance.

Fosberg, Michael A. 1977. Heat and water transport properties in conifer duff and humus. USDA For. Serv. Res. Pap. RM-195, 10 p. Rocky Mt. For. and Range Exp. Stn. Fort Collins, Colo.

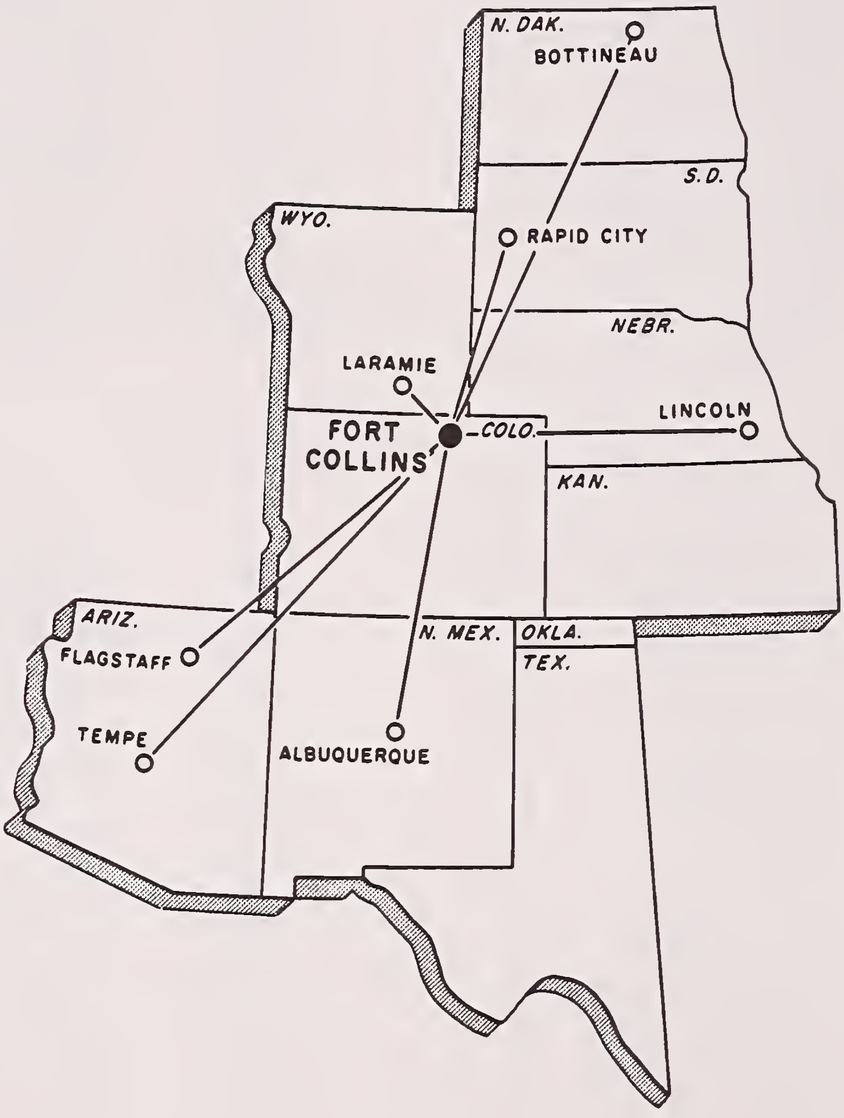
Permeability and bulk densities of duff and humus in stands of ponderosa pine, lodgepole pine, and Douglas-fir were measured to provide a data base for fuel moisture and soil infiltration models. Diffusion of heat and water vapor through a ponderosa pine duff layer was measured to calibrate a diffusion model. These results provide necessary data and relationships required by complex forest soil water balance and energy models.

Keywords: Fuel moisture, soil infiltration, soil water balance.

Fosberg, Michael A. 1977. Heat and water transport properties in conifer duff and humus. USDA For. Serv. Res. Pap. RM-195, 10 p. Rocky Mt. For. and Range Exp. Stn. Fort Collins, Colo.

Permeability and bulk densities of duff and humus in stands of ponderosa pine, lodgepole pine, and Douglas-fir were measured to provide a data base for fuel moisture and soil infiltration models. Diffusion of heat and water vapor through a ponderosa pine duff layer was measured to calibrate a diffusion model. These results provide necessary data and relationships required by complex forest soil water balance and energy models.

Keywords: Fuel moisture, soil infiltration, soil water balance.



N. DAK.
BOTTINEAU
S.D.
WYO.
RAPID CITY
NEBR.
LARAMIE
LINCOLN
FORT
COLLINS
COLO.
KAN.
ARIZ.
N. MEX.
OKLA.
TEX.
FLAGSTAFF
TEMPE
ALBUQUERQUE